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Numerical and experimental investigations on two-phase flow of liquid nitrogen in a flexible transfer line

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Abstract. Transfer of cryogenic fluids is a daily occurrence in laboratories and industries for various end applications. Vacuum or super insulated transfer lines are generally used to transfer cryogenics to minimize the evaporation due to heat transfer. Because of the heat transfer and the nature of flow, most of the time two-phase flow occurs during the transfer of cryogenics. It is necessary to estimate the amount of cryogen being evaporated and the quality of the flow in the transfer process. This paper deals with the numerical and experimental investigations on the two-phase flow behaviour of liquid nitrogen transfer through the developed flexible transfer line. Diode based liquid level sensors have been developed to measure the void fraction of the two-phase flow. The numerical and the experimental results are in good agreement with each other. Pressure drop and cool-down data of the transfer process is also presented in the paper.

1. Introduction

Transfer of cryogenic fluids from the storage Dewar's to the end applications is a daily occurrence in laboratories and industries. Vacuum or super-insulated transfer lines are more efficient for the above applications. Vacuum-insulated lines consist of an inner pipe, in which the liquid flows; concentric to it is an outer vacuum jacket. The annular space may contain vacuum alone or vacuum with multilayer insulation known as super-insulation. Flexible transfer lines have more maneuverability though the heat transfer is little higher compared to rigid transfer lines. To our knowledge, not much open literature is available on the design of such flexible transfer lines. Hence, an attempt has been made to design and develop a flexible transfer line of ~ 3 m long for liquid helium applications. Studies on pressure drop, cool-down and void fraction has been done for this transfer line with liquid nitrogen (LN₂) as the working fluid. The 3-D CAD model of the developed vacuum insulated flexible transfer line is shown in figure 1.

2. Design and development of the transfer line

The flexible transfer line has been designed for 2 to 15 liters per minute (LPM) of LN₂ flow rates. The diameters and the wall thicknesses for the inner and the outer bellows have been calculated according to American Standard code for pressure piping and selected to the standard schedules [1-2]. The inner bellow is made of AISI SS-304L material with 20.5 mm ID and 26.8 mm OD whereas the outer bellow is made of AISI SS-304 material with 51 mm ID and 62.1 mm OD. The wall thickness of both the bellows is 0.3 mm. The outer bellow is braided with 1 mm diameter SS wires.



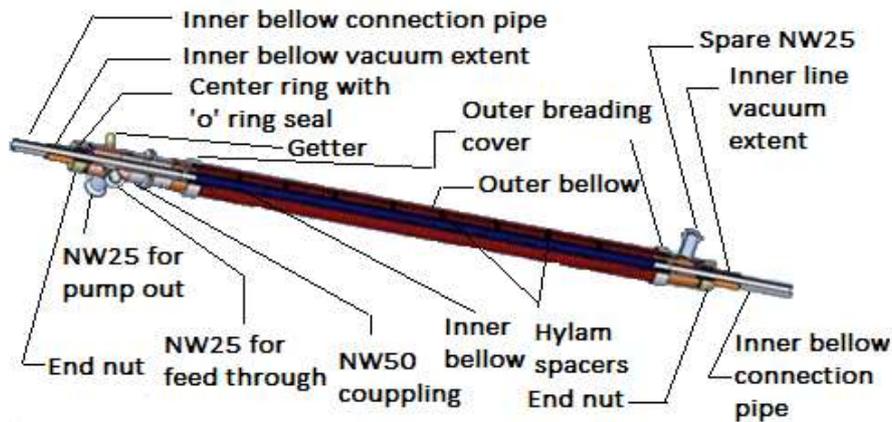


Figure 1. 3-D CAD model of the developed flexible transfer line.

Hylam™ spacers have been used to maintain the inner bellow concentric to the outer bellow. The transfer line has been designed in such a way that it can be quickly dismantled and reassembled with the help of the O-rings and the lock nuts provided at both the ends. This enables to evaluate the performance of the developed transfer line for cool-down and two-phase flow (void fraction) of the cryogenic fluid for vacuum and super-insulated conditions. The end couplings have connections for feed through, getter and pump out port. The photograph of the developed transfer line is shown in figure 2.



Figure 2. Photograph of developed flexible transfer line.

3. Pressure drop studies

Many correlations are available to determine the two phase pressure drop, among that of Lockhart-Martenelli correlation which is simple and best to determine the theoretical two phase pressure drop [3]. Frictional pressure drop and pressure drop due to corrugations can be found out by considering coefficient of friction and minor loss co-efficient (eq.1). Most of the time, there exist two-phase flow in cryogenic transfer lines. The separated-flow model is used to determine the two-phase pressure drop (eq. 2).

$$\left(\frac{\Delta P}{No. \text{ corrugations}}\right) = \left(\left(\lambda * \left(\frac{1}{D_{1in}} \right) \right) + \tau \right) \frac{\rho * V^2}{2} \quad (\text{eq.1})$$

$$\left(\frac{\Delta P}{\Delta L}\right)_{TP} = \phi^2 \times \left(\frac{\Delta P}{No. \text{ corrugations}}\right)_L \quad (\text{eq.2})$$

$$\text{where, } \phi = \frac{(X^2 + CX + 1)^{1/2}}{X} \quad (\text{eq.3})$$

$$\text{and } X^2 = \frac{C_L (Re_V)^m \rho_V}{C_V (Re_L)^n \rho_L} \left(\frac{1-x}{x}\right)^2 \quad (\text{eq.4})$$

Where, D_{in} = Inner diameter of inner bellow, λ = Coefficient of friction (= 1.6 for zero bending radius), τ = Resistance coefficient (= 0.0625 if $10^5 < Re < 10^4$, 0.08 if $Re > 10^5$), ρ = Density of liquid in kg/m^3 , V = Velocity of flow in m/s, Re = Reynolds number and C , C_L and C_V are constants and depends on the type of vapor and liquid flow. Subscripts V and L represents vapor and liquid respectively [2]. By the above correlations, the theoretical pressure drop, $(\Delta P)_{TP}$ found to be 15395 Pa for 10 LPM of LN_2 flow rate.

4. Experimental setup and results

The schematic of the experimental setup is shown in figure 3. The developed transfer line is mounted horizontally between the supply and the collection Dewars. The Dewars are mounted on the load cells to measure the mass flow rates through the transfer line which mainly depend on the pressure of the supply dewar [4]. Rotary and turbo pumps are used to evacuate the transfer line to $\sim 4.3E-5$ mbar. The fluid coming out from the transfer line is collected in the pre-cooled collection Dewar. Two pressure transducers are installed near the inlet and outlet of the transfer line. The axial temperature profile of the inner line from the start of cool-down to the steady state condition is measured by PT-100 temperature sensors mounted on the outer surface of the inner bellow and Scientific Instruments temperature indicator M-9308. The cool-down and pressure drop data is recorded using National Instruments cDAQ card and LabVIEW-V2017 program.

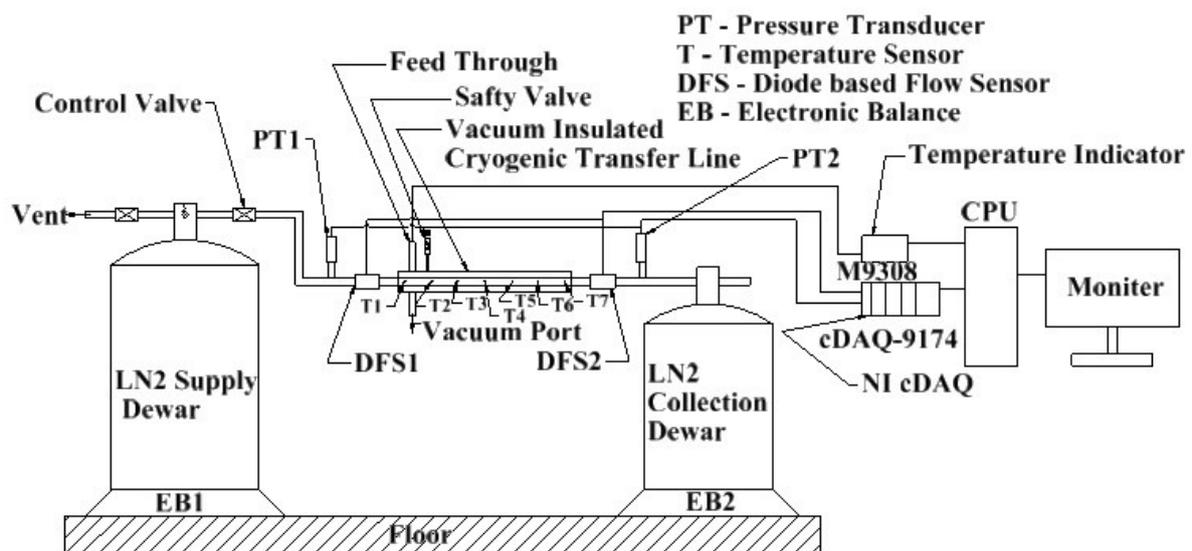


Figure 3. Schematic of experimental setup.

The pressure drop recorded by the experimental setup is about 15680 Pa for 10 LPM of LN_2 flow rate. The cool-down of the transfer line for the above flow rate is shown in figure 4.

5. Void fraction measurement

The void fraction can be determined by various techniques such as Gama ray absorption, X-ray absorption, impedance, optical void probes, capacitive measurement technique and diode based measuring technique [5-6]. Though capacitance type measurement technique is most common, it is not easy to manufacture such sensors for cryogenic fluids. In view of the above, an attempt has been made to develop diode based sensor to determine the two-phase flow characters of the cryogenic fluids in the developed transfer line. The developed diode based sensor is shown in figure 5 and 6.

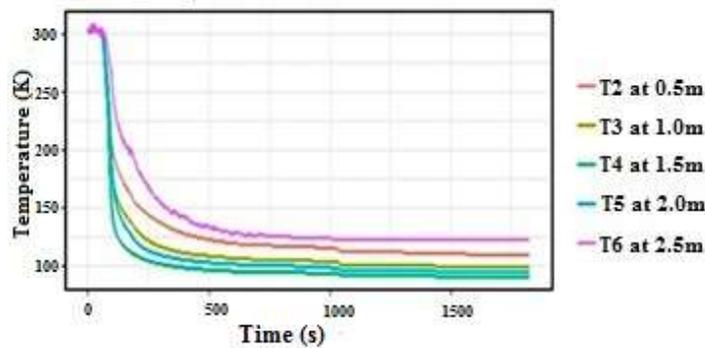


Figure 4. Cool-down of vacuum jacketed flexible transfer line.

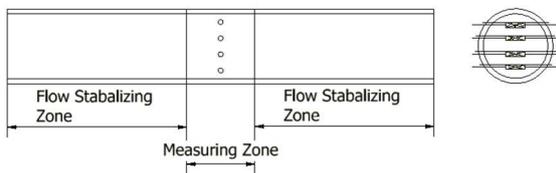


Figure 5. 2-D view of diode based void fraction measuring sensor.

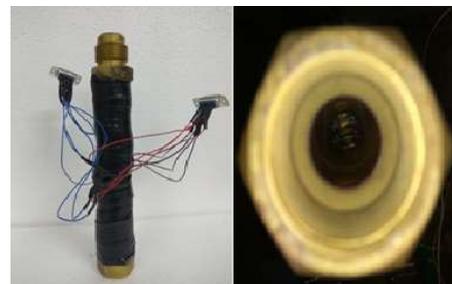


Figure 6. Photograph of diode based void fraction measuring sensor.

The sensor consists of 4 diodes (1N4148) mounted across the diameter of the copper pipe along the transverse direction of the flow. Sensors have been mounted in the flow measuring zone. Nickel-chromium alloy wire is wound over the diodes to heat towards fast respond for the change in liquid flow patterns. Schematic of diode based void fraction measurement system is shown in figure 7. Bias current source is used to heat the nickel-chromium alloy (heater) wires. Switching circuit is used to switch the diodes one by one for fluid quality measurement. The circuit diagram for switching the diodes is shown in figure 8. DC voltage source is used to supply the voltage to switching circuit.

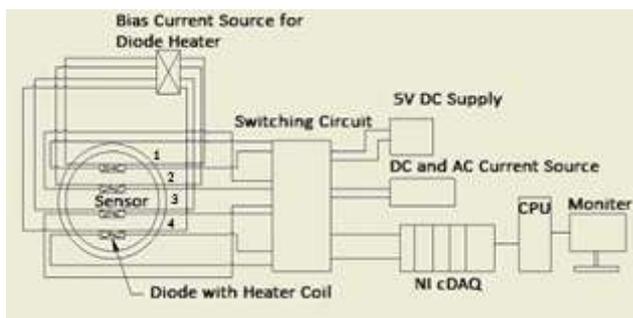


Figure 7. Schematic of diode based void fraction measurement system.

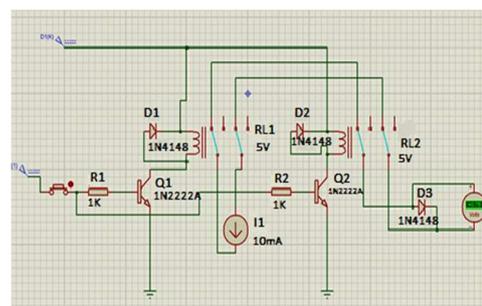


Figure 8. Circuit diagram for switching the diodes.

Relays are used to switch the diodes one by one with the help of NI-cDAQ and LabVIEW V2017 programming. Diodes D1 and D2 are flyback diodes for relays RL1 and RL2 respectively. Diode D3 is used to find the fluid quality. When the relays RL1 and RL2 is switched on 10 mA current flows from I1 through the diode D3 and gives output voltage according to the fluid quality. Output voltage from the diode is read by the NI cDAQ and displays the voltage in the monitor screen.

The output voltage is of 0.65 V at room temperature, 0.77 V when diode is exposed to cold nitrogen vapor and 1.04 V when diode is in contact with LN₂. Void fraction is measured by the level of liquid in the measuring zone. The diode 1 measures the void fraction range from 0 to 0.16, the diode 2 measure the void fraction range from 0.17 to 0.39, the diode 3 measure the void fraction range from 0.4 to 0.71 and the diode 4 measures the void fraction range from 0.72 to 0.92. At steady state condition, the readings corresponding to the void fraction is recorded. It is observed that the top diode of the diode sensor fluctuates in the voltages range of 0.77 V and 1.04 V. Remaining 3 diodes shows constant voltage of 1.04 V. From the above data it is observed that two-phase flow corresponds to wavy flow pattern. The void fraction measured by the diode sensor ranges from 0.17 to 0.39. Diode based void fraction measurement is a discreet measurement technique which gives a range of the actual void fraction. Increasing the number of diodes may decrease the range and increase the accuracy of measurement. With the help of this simple sensor we could identify the mist flow, slug flow, annular flow and wavy flow during the transfer process.

6. Fluid flow analysis of the transfer line

2-D model of flexible transfer line is made using ANSYS Fluent-17 work bench to perform two-phase flow analysis. Meshing has been done with the ANSYS meshing tool. K-epsilon model is used for simulation. Initial and final boundary conditions are applied from the experimental data. LN₂ flow at 77 K is assumed through the transfer line. Heat loads at both the ends are applied and initialized the solution. The temperature plot and void fraction as obtained through the analysis is shown in figure 9 and 10 respectively. The two-phase pressure drop is found to be 13272 Pa and quality factor(X) is 0.19. The simulation results are within the range of experimental measured data.

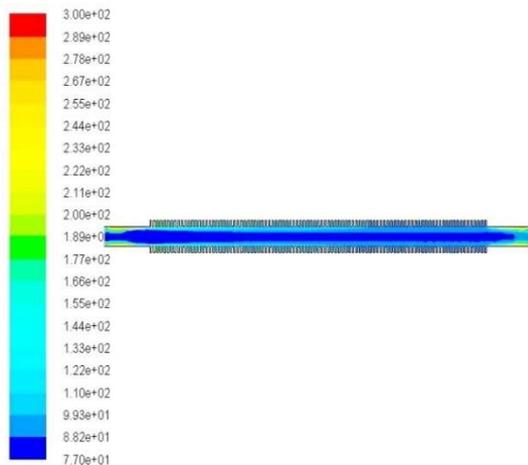


Figure 9. Temperature plot inside the flexible transfer line.

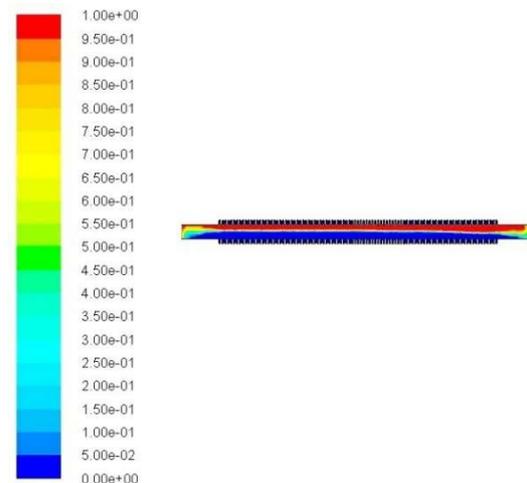


Figure 10. Void fraction distribution inside the flexible transfer line.

Temperature profile and pressure drop values are found to be little less than experimental data as radiation heat load is not considered for analysis. The comparison of temperature profile between the CFD analysis and experimental results is shown in the figure 11 and in good agreement with each other.

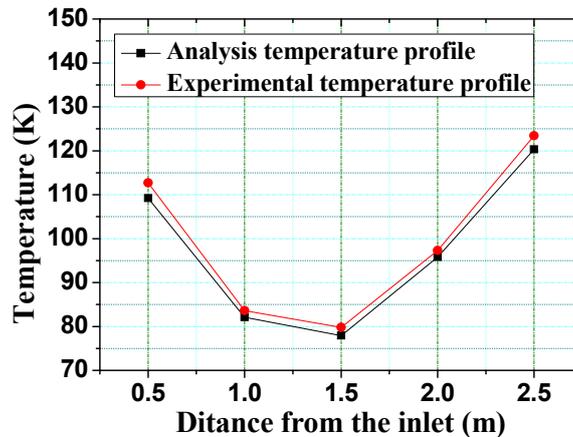


Figure 11. Temperature profile comparison.

7. Conclusion

A flexible transfer line of ~ 3 m long and 20.5 mm ID has been designed and developed. The cool-down characteristics have been evaluated through experimental studies. Theoretical, numerical and experimental pressure drops are 15395 Pa, 13272 Pa and 15680 Pa respectively for the two-phase flow of LN₂ and are in good agreement with each other. For the first time, a diode based void fraction measurement sensor has been developed which could measure the quality of the flow. The temperature profile and the void fraction distributions obtained by fluid flow analysis matches well with the experimental results. The studies will be very useful for design of flexible transfer lines for liquid helium applications and measurement of void fraction for cryogenic two-phase flow by simple diode sensors.

References

- [1] N. Dittmar et al, 2016. *Cryogenics*, Vol.75, pp. 6-12
- [2] Randall Barron, 1985 *Cryogenic systems*, 356-427, ISBN 13: 9780195035674
- [3] G K Singh et al, 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* 171 012061
- [4] Krishna Murthy, M. V., Srinivasa Murthy, S., Srinivasan, K., Kanniah, M., 1976. *Cryogenics*, Vol.16, pp. 409-412
- [5] Yu. P. Filippov, 2001. *Cryogenics*, Vol. 41, pp. 327-334
- [6] Abhay Singh Gour et al, 2017. *Cryogenics*, Vol.84, pp. 76-80